# Validation of satellite-retrieved oceanic inherent optical properties: proposed two-color elastic backscatter lidar and retrieval theory

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Recent radiative transfer models show that: (1) regardless of elastic lidar receiver field of view (FOV), at vanishing lidar depth the lidar-derived attenuation coefficient $k_{\mathrm{lidar}} \rightarrow a$, where $a$ is the total absorption coefficient per meter of depth; and (2) for a wide FOV as the lidar sensing depth approaches some large value (depending on water type), $k_{\mathrm{lidar}} \rightarrow K_d$, where $K_d$ is the diffuse attenuation for downwelling irradiance. As a result, it is shown that a time-resolved, dual-wavelength-laser, elastic-backscattering lidar can retrieve the three principal oceanic optical properties: (1) the absorption coefficient of phytoplankton $a_{\mathrm{ph}}$, (2) the absorption coefficient of chromophoric dissolved organic matter (CDOM) $a_{\mathrm{CDOM}}$, and (3) the nonwater total constituent backscattering coefficient $b_{\mathrm{bt}}$. The lidar-retrieved $a_{\mathrm{ph}}$, $a_{\mathrm{CDOM}}$, and $b_{\mathrm{bt}}$ inherent optical properties can be used to validate corresponding satellite-derived products such as those from terra moderate-resolution imaging spectroradiometer (MODIS), Aqua MODIS, Sea-viewing Wide Field-of-view Sensor, (SeaWiFS), and other ocean color sensors. © 2003 Optical Society of America

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## 1. Introduction

Terra MODIS (moderate-resolution imaging spectroradiometer), Aqua MODIS, and Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) satellite-derived water-leaving reflectances allow the retrieval of absorption coefficients of phytoplankton $a_{\mathrm{ph}}$ and chromophoric dissolved organic matter (CDOM) $a_{\mathrm{CDOM}}$. The retrieval algorithms for these satellite inherent optical properties (IOPs) are routinely developed and validated with a robust airborne lidar fluorosensor.[1–4] However, there are several plausible reasons to suggest the development of a dual-laser elastic lidar. First, for those laboratories having limited resources, an elastic lidar can potentially provide a more economical alternative to a fluorescence lidar, i.e., only two elastic receiver channels are required to retrieve the three principal IOPs (and this can be further reduced to only one channel if a fiber-optic delay segment can be implemented from channel 2 of the spectrometer into the channel 1 photodetector). Second, the elastic radiative transfer physics is more fully developed (in contrast to the present redshifted empirical phytoplankton and CDOM absorption surrogates composed of inelastic fluorescence/Raman ratios). Better modeling and understanding of the elastic lidar returns leads to a better understanding of the fluorescence and Raman emissions as well. Third, a rather wide range of elastic transmit wavelengths can be used for the IOP retrievals (while, if desired, concurrently allowing for more optimum excitation of taxanomically important phytoplankton fluorescence and spectral placement of the water Raman emissions). Fourth, presently, the backscattering coefficient is not obtainable from fluorescence or Raman emissions but would be available from an elastic lidar configuration.

Thus the objective of this paper is to propose a dual-laser elastic-backscattering lidar configuration and theory for (1) retrieval of the total absorption coefficient $a$ (and the resulting $a_{\mathrm{ph}}$ and $a_{\mathrm{CDOM}}$ components) and (2) the diffuse attenuation for downwelling irradiance $K_d$ (and the resulting nonwater total constituent backscattering $b_{\mathrm{bt}}$ due to particles, large molecular weight molecules, and colloid suspensions).[1–3] In addition to the two laser wavelengths, the third degree of freedom required for retrieval of three IOPs is furnished by the temporal measurement.

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## 4. Summary and Discussion

Analytic lidar equations[5] based on a robust beam-spread function with time dispersion[13] show that, regardless of FOV, $k_{\text{lidar}} \rightarrow a$ in the limit of vanishing depth. For hardware implementation, a narrow-FOV configuration is not recommended because of high uncertainty in $k_{\text{lidar}}$ as null depth is approached. The more desirable wide-FOV configuration can be applied during nighttime operations but probably requires multiple FOV segments to limit daytime background noise.

Dual-laser lidars yield two total absorption values that can be solved by linear methods to provide the main oceanic absorption coefficients: phytoplankton absorption coefficient $a_{\text{ph}}$ and CDOM absorption coefficient $a_{\text{CDOM}}$.

In the limit of large depth, the wide-FOV lidar yields $K_d$, the diffuse attenuation coefficient for downwelling irradiance. $K_d$ provides the total backscattering coefficient by $b_b = K_d - a$ or the total constituent backscattering from $b_{\text{bt}} = K_d - a - b_{b\text{,water}}$. Thus the three main oceanic IOPs ($a_{\text{ph}}$, $a_{\text{CDOM}}$, $b_{\text{bt}}$) are retrievable with a dual-laser wide-FOV elastic-backscattering lidar having wide-bandwidth time and depth digitizers. These three IOPs are the same as obtained from satellite-derived passive water-leaving radiances[1–3] and, accordingly, can be validated by airborne underflights with a dual-laser wide-FOV elastic-backscattering lidar system. Because the optical coefficients are derived for two different depths, this implies that the water column is uniformly mixed. If this oceanic physical condition is not met, then undetermined errors should be expected. Undesired water column nonuniformity can be detected when the entire water column return is analyzed.[14]

The Walker and McLean[5] findings also show that, in the limit of small FOV, $k_{\text{lidar}} \rightarrow c$, the beam attenuation, for certain intermediate depths between $\zeta \sim 0$ and $\zeta = \zeta_{K_d}$ required for the respective retrieval of $a$ and $K_d$. If the proper depth for beam attenuation $\zeta_c$ can be accurately determined, then $c$ can be further used to retrieve the forward-scattering coefficient $b_f = c - a - b_b$ where $a$ and $b_b$ were previously determined at $\zeta \sim 0$ and $\zeta = \zeta_{K_d}$, respectively. The $b_f$ optical property is infrequently retrieved by remote sensing but is required in newer-generation remote sensing reflectance models[15,16] that are based on the radiative transfer equation. The beam attenuation coefficient alone is a highly important IOP because it is strongly correlated with particulate organic carbon,[17,18] a notable component of the global oceanic carbon cycle. Other researchers[19] findings agree with Walker and McLean[5] for the so-called coherent or beam attenuation component of the lidar return.

Even after several decades, the most fundamental elastic lidar measurement, depth sounding, is still performed with considerable attention to details.[20–22] Thus one should not expect instant success with the IOP retrieval methods proposed here. Inelastic lidar fluorosensors are less prone to some of the challenges of elastic lidars because their redshifted returns are volumetric and show significantly less air–water interface effects. Accordingly, nonempirical radiative-transfer-based algorithms must eventually be sought for the inelastic lidar return signals. In this regard, it is recommended that the Walker and McLean[5] analyses be extended to the OH-stretch water Raman signal now observed routinely with airborne oceanic lidars.[1–4] Then a single-laser lidar could be used to retrieve the three principal oceanic IOPs: phytoplankton and CDOM absorption and the constituent backscattering coefficients. For example, a 532-nm lidar should have at least two receiver channels: the usual 532-nm elastic channel and an inelastic $\sim$3250-cm$^{-1}$ OH-stretch water Raman band at $\sim$645 nm. A 355-nm laser lidar should have at least three receiver channels: the usual 355-nm elastic channel, a water Raman band at $\sim$402 nm, and a 450-nm channel to provide for CDOM fluorescence removal from the 402-nm Raman emission band. Because the 532- or 355-nm laser wavelengths are nonoptimal, a tunable laser set to $\sim$443 nm for phytoplankton and CDOM absorption would seem ideal and would produce a water Raman emission at $\sim$518 nm. A third band at perhaps $\sim$490 nm (to acquire CDOM fluorescence to produce corrections for the Raman band) would be required. Laboratory experiments are recommended to finalize these band selections.

To implement the methods outlined here, commercially available lasers, telescopes, and time digitizers are generally suitable. However, initially, this proposed lidar IOP retrieval concept might be tested with only a single wide-FOV receiver during nighttime flights of an existing airborne lidar. Such a configuration would require minimum hardware and may provide basic information that would allow a daytime wide-FOV system to be implemented. For example, a single wide FOV for nighttime flight could potentially be implemented on an existing lidar such as the NASA AOL with relative ease. The NASA AOL-III[4] is a dual-laser lidar (and carries ancillary passive ocean color and infrared radiometers) and could conceivably be retrofitted with dual rotating disk MFOV segments to measure $a$ at both 355 and 532 nm during daytime. The AOL already possesses high-speed waveform digitizers to acquire lidar return waveforms for retrieval of both $a$ and $K_d$. These elastic retrievals at 355 and 532 nm would then complement the standard inelastic phytoplankton and CDOM fluorescence products.[1,2,4] Initially, during application of a dual-laser elastic lidar, the resulting IOP retrievals should be validated with both supporting ship measurements and inelastic fluorosensor lidar findings. However, it is also suggested and recommended that initial validation of the above elastic lidar-derived products be accomplished with an airborne passive nadir-viewing ocean color spectroradiometer. The NASA AOL's companion Airborne Diode Array Spectroradiometer (ADAS) is an example of a suitable spectroradiometer.